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SOLAR ACCESS AND ENERGY GAIN OF THE BUILDINGS IN A DENSELY BUILT URBAN AREA

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Abstract:
The aim of our research is to calculate the solar irradiance assuming clear sky conditions for the inner city of Szeged. The basis of the calculations is the 3D building database of Szeged, which contains more than 22 000 elements. Before the radiation calculation this vector based database had to be converted to a raster based digital surface model. This model similar to the digital elevation models (DEM) and it contains not only the natural relief, but also the buildings. The calculations were carried out using the exposure of the roofs of individual buildings firstly as separate elements and secondly, including the shading effect of the surrounding buildings as well. With the comparison of the two outputs we can reveal the effect of the mutual shading on the possible solar energy gain of the building roofs in urban areas.

1. Introduction

The solar radiation as a renewable energy could be a significant energy source in urban environments which are the main energy users concentrating on relatively small areas compared to the total Earth’s surface. This locally produced energy applying active and passive solar systems installed on roofs and walls has very short transport “routes” therefore the energy loss by transport is negligible, so it can contribute significantly to the energy demand of buildings. This demand is in very close connection with the heat output of buildings whose magnitude changes seasonally and in certain periods it can exceed the daily solar radiation input primarily in the densely built up inner city areas (Seprődi-Egeresi and Zöld, 2011).

The amount of solar energy reaching the surface at a place depends on mainly natural factors: seasonal change of the Earth-Sun geometry, location of the place, atmospheric conditions as a function of local weather and climate, as well as air pollution. Additionally, as the urban surface geometry is very complex mainly because of the houses and buildings with different heights and their uneven spatial distribution, the mutual shading of the buildings also influences the possible energy gain of the solar systems.

There are several existing methods for the calculation of direct and diffuse solar irradiance for natural relief (Hetrick et al., 1993, Kumar et al., 1997), but the application of these methods for urban areas (including the building walls and roofs) is rare. This study is a first step of a longer research directed on urban areas’ utilized solar energy gain. Now we assume cloudless sky conditions in order to reveal the quantitative effect of mutual shading of the buildings on the possible maximum amount of the solar energy input on roofs in the case of a Central-European city, Szeged, as an example.

2. Study area and applied methods

2.1 Study area and the digital surface model

Szeged (46ºN, 20ºE) is located in southeast Hungary at 79 m above sea level on a flat plain (Figure 1). According to Trewartha’s classification the city belongs to the climatic type D.1 (continental climate with longer warm season), similarly to the predominant part of the country (Unger, 1996). The urbanized area of Szeged is around 50 km^2 and its avenue-boulevard street network was built to follow the axis of the river Tisza. There are no other large water bodies in the vicinity of the city.

The so called calculation area overlaps the city core (Figure 1) with an extension of 630 425 m^2 (~0.6 km^2) and within this area the footprints of the buildings cover 199 160 m^2. The height of the buildings in the city core is rather homogenous, the average height is 13 m, however, there are a few 10-story buildings. In the centre of the calculation area we selected a smaller study area (230 m x 160 m = 36 800 m^2) (Figure 1) in order to illustrate the effect of mutual shading of the buildings with different heights (the range is between 6 and 35 m).

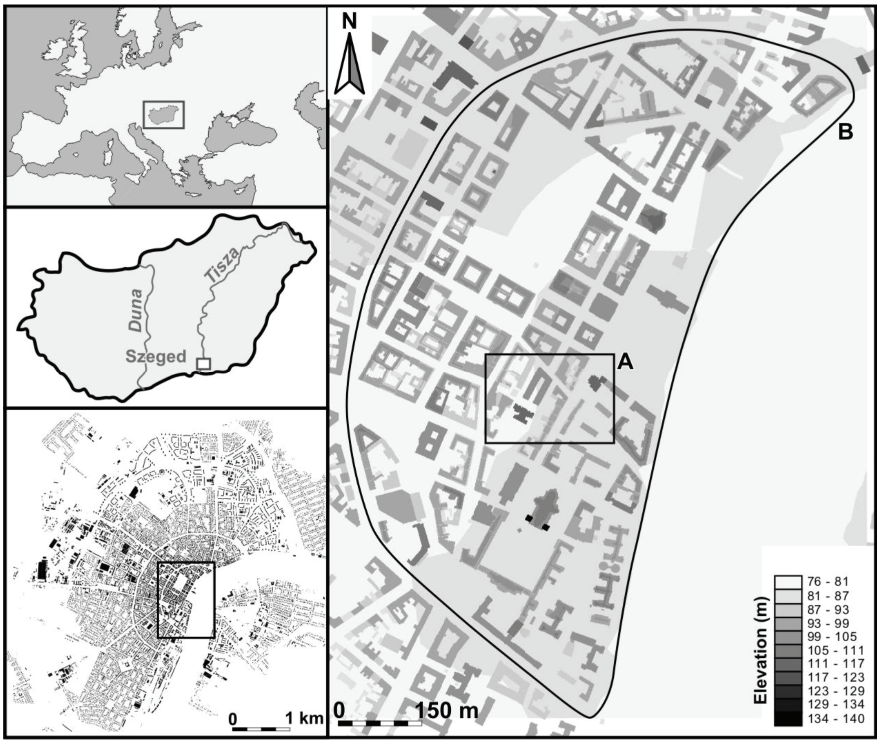

Figure 1: The location of the study area (A) and the calculation area (B), in Szeged, Hungary

For the calculation of the solar radiation a digital surface model is necessary. This surface model has to contain the natural relief and the buildings’ envelope. For the calculation area we created this surface model using the Digital Elevation Model (DEM) of Szeged which represents a bare surface with a small vertical variation of the surface (75.5–83 m a.s.l.) and the 3D building database for Szeged. This 3D database is based on local municipality data of building footprints and the building height information measured from aerial photographs using photogrammetry method (Unger, 2006). For all of the buildings the location of the ridges and eaves were digitized. To represent the building envelopes a Triangular Irregular Network (TIM) was created based on the building footprint, the lines of the ridges and eaves and their elevations using ArcView 3D Analyst (www.esri.com). Finally the buildings’ TIM and the DEM were converted to raster based Esri Grid files and these two grids have been combined. The final 0.5 m resolution digital surface model contains the natural surface and the complete building envelope, and using this model the surface characteristic (e.g. slope, aspect) can be taken into account for the calculation of the irradiance (Figure 2).

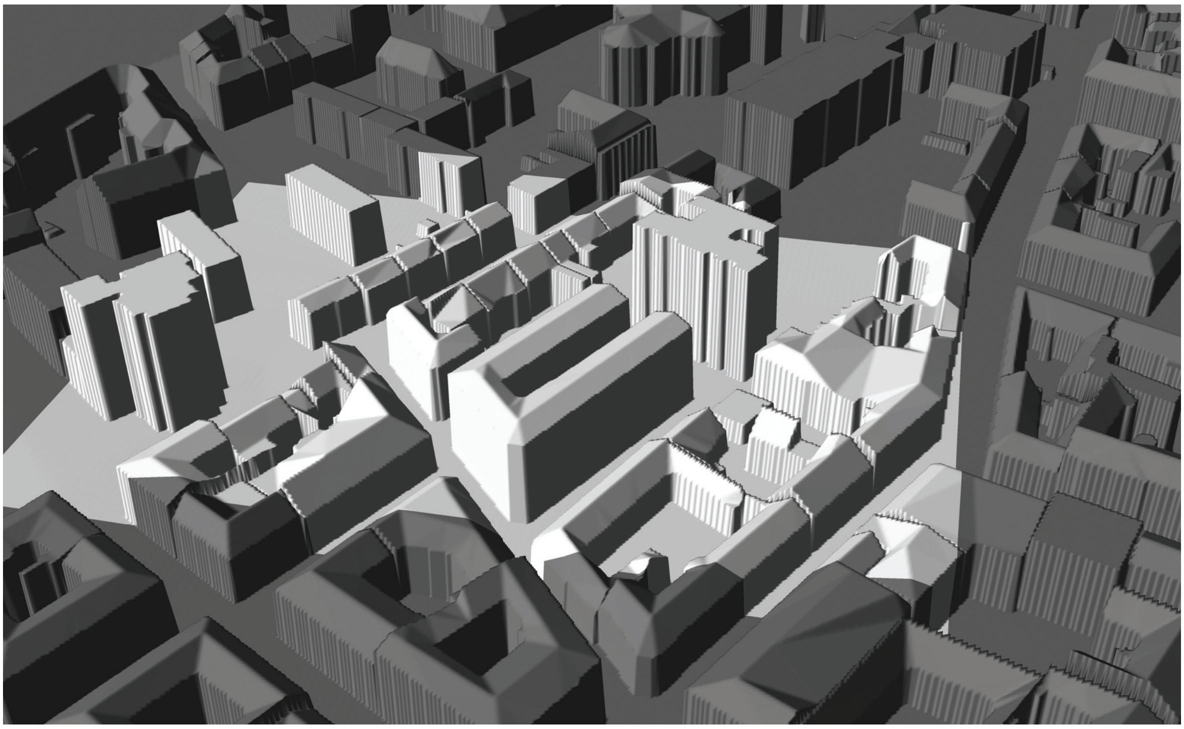

Figure 2: The digital surface model of the study area and its surroundings in Szeged, Hungary (seeing from north)

2.2 Calculation of the daily amount of solar input

The daily irradiation was calculated using algorithm coded in ArcView GIS system's built-in object-oriented script language (Avenue) (www.esri.com).

For the calculation of the flux density and amount of the solar radiation the Sun's position is needed at the calculation time. The position of the Sun can be determined by the solar altitude angle (h_{sun}) which is the angular elevation of the Sun above the horizon, and the solar azimuth angle (a_{sun}) which is angular distance between the horizontal projection of the direction of the Sun and the direction of South. The solar altitude angle and the solar azimuth angle were calculated by the following equations (Robinson, 1966):

$$\sin h_{sun} = \sin\varphi \cdot \cos\delta_{sun} + \cos\varphi \cdot \cos\delta_{sun} \cdot \cos\omega_{sun} \tag{1}$$

$$\sin a_{sun} = \frac{\cos\delta_{sun} \cdot \sin\omega_{sun}}{\cos h_{sun}} \tag{2}$$

where φ is the latitude of the site, δ_{sun} is the solar declination and ω_{sun} is the hour angle of the Sun. The solar declination varies from -23,45° to 23,45° and it can be calculated by the equation 3 if the number of the day (N) in the year is known (Kumar et al., 1997).

$$\delta_{sun} = 23.45 \cdot \sin\left(360 \cdot \frac{284 + N}{365}\right) \tag{3}$$

The other key parameter for the calculation of insolation in tilted surfaces is the angle (i) between the direction of the Sun and normal of the slope. It can be calculated by the equation 4 (Bencze et al., 1982).

$$\cos i = \cos h_{slope} \cdot \sin h_{sun} + \sin h_{slope} \cdot \cos h_{sun} \cdot \cos\left(a_{sun} - a_{slope}\right) \tag{4}$$

where h_{slope} is the slope angle of each grid point and a_{slope} is the slope aspect in each grid point (0° is referred to South direction). The slope angle and the aspect are calculated with the built in function of Avenue script language using the raster format digital surface model of the study area.

The solar radiation received at the outer edge of the atmosphere is the solar constant (I_0) and according to the different measurements its value varies from 1353 Wm^{-2} (Jansen, 1985) to 1373 Wm^{-2} (Monteith and Unsworth, 1990). We used 1367 Wm^{-2} for the calculation as it is a widely accepted value (Duncan et al., 1982, Wherli, 1985, Kumar et al., 1997). The solar radiation is reduced by the atmosphere while it reaches the surface. This attenuation depends on the air mass ratio (M) and the atmospheric transmittance (τ). The air mass ratio describes the relative mass of air which the solar beam has to pass trough and it can be calculated by the equation 5, while the atmospheric transmittance is determined by the equation 6 assuming clear weather conditions (Kreith and Kreider, 1978).

$$M = \sqrt{1229 + \left(614 \cdot \sin h_{sun}\right)^2} - 614 \cdot \sin h_{sun} \tag{5}$$

$$\tau = 0.56 \cdot \left(e^{-0.65M} + e^{-0.095M}\right) \tag{6}$$

Using the calculated input values the direct (I_{dir}), diffuse (I_{diff}) and reflected radiation (I_{refl}) fluxes are calculated for each grid point with the help of equations 7, 8 and 9 (Gates, 1980).

$$I_{dir} = I_0 \cdot \tau \tag{7}$$

$$I_{diff} = I_0 \cdot (0.271 - 2.294 \cdot \tau) \cdot \cos^2 \frac{h_{slope}}{2} \cdot \sin h_{sun} \tag{8}$$

$$I_{refl}l = 0.15 \cdot I_0 \cdot \left(0.271 + 0.706 \cdot \tau\right) \cdot \sin^2 \frac{h_{slope}}{2} \cdot \cos h_{sun} \tag{9}$$

In order to quantify the effect of the shading of buildings for the solar access to other buildings we calculated the global radiation ($K\downarrow$) values by grid points distinguishing two cases. In the first case ($K\downarrow_{no\text{-}shade}$) the shading effect of the surrounding buildings was not take into consideration, the calculation of the irradiance is taken by adding the three terms according to the equation 10. In the second case ($K\downarrow_{shade}$) we localized the area of the shadows of the buildings using the hill shade function (which is a built in function of Avenue script language) and for the shaded grid points the $K\downarrow$ was calculated by the equation 11, and for the not shaded ones by equation 10.

$$K\downarrow = I_{dir} + I_{diff} + I_{refl} \tag{10}$$

$$K\downarrow = I_{diff} + I_{refl} \tag{11}$$

The daily irradiance was calculated by 30 minute time steps in the case of some distinctive days of year (solstices and equinoxes). At equinoxes in March and September the diurnal movement of the Sun and therefore the characteristics of the irradiance are the same, so we obtained 3 result maps.

3. Results

Figure 3. shows the spatial distribution of the calculated daily amount irradiance in the study area at the selected days. In summer the maximum occurs mostly in roofs with south aspect (Figure 3.A). Due to the high angular elevation of the Sun the shadows of the buildings do not affect the irradiation on all of the roofs, however in the centre of the area there are two higher buildings and northwest from these buildings the daily irradiance decreases by approximately 10 MJm^{-2} in the nearest roofs (Figure 3.D). In autumn and spring the spatial distribution of the difference is similar

(Figure 3.E), but the proportion of this solar input loss is higher due to the lower maximum irradiation (Figure 3.B). In winter the shadows decrease the irradiation at almost all of the buildings and the ratio of the difference reaches of 1/3 of the total irradiance in large areas (Figure 3.F).

The descriptive statistics of the calculated daily amounts of the irradiance ($K\downarrow_{shade}$) and the irradiation loss ($K\downarrow_{no\text{-}shade} - K\downarrow_{shade}$) help us to understand the effects of the roof orientation and the shading on the potential energy gain of the buildings (Table 1). In summer the highest values are 67% higher than the average of the calculated values so using this method we can localize the most suitable places for installing active or passive solar systems on roofs. So, if we select a place based on only the aspect and angle of the roof we may find an unsuitable place because the mean effect of the shading in the study area is about 2.0-2.5 MJm^{-2} and it means a significant loss in the amount of the incoming solar energy.

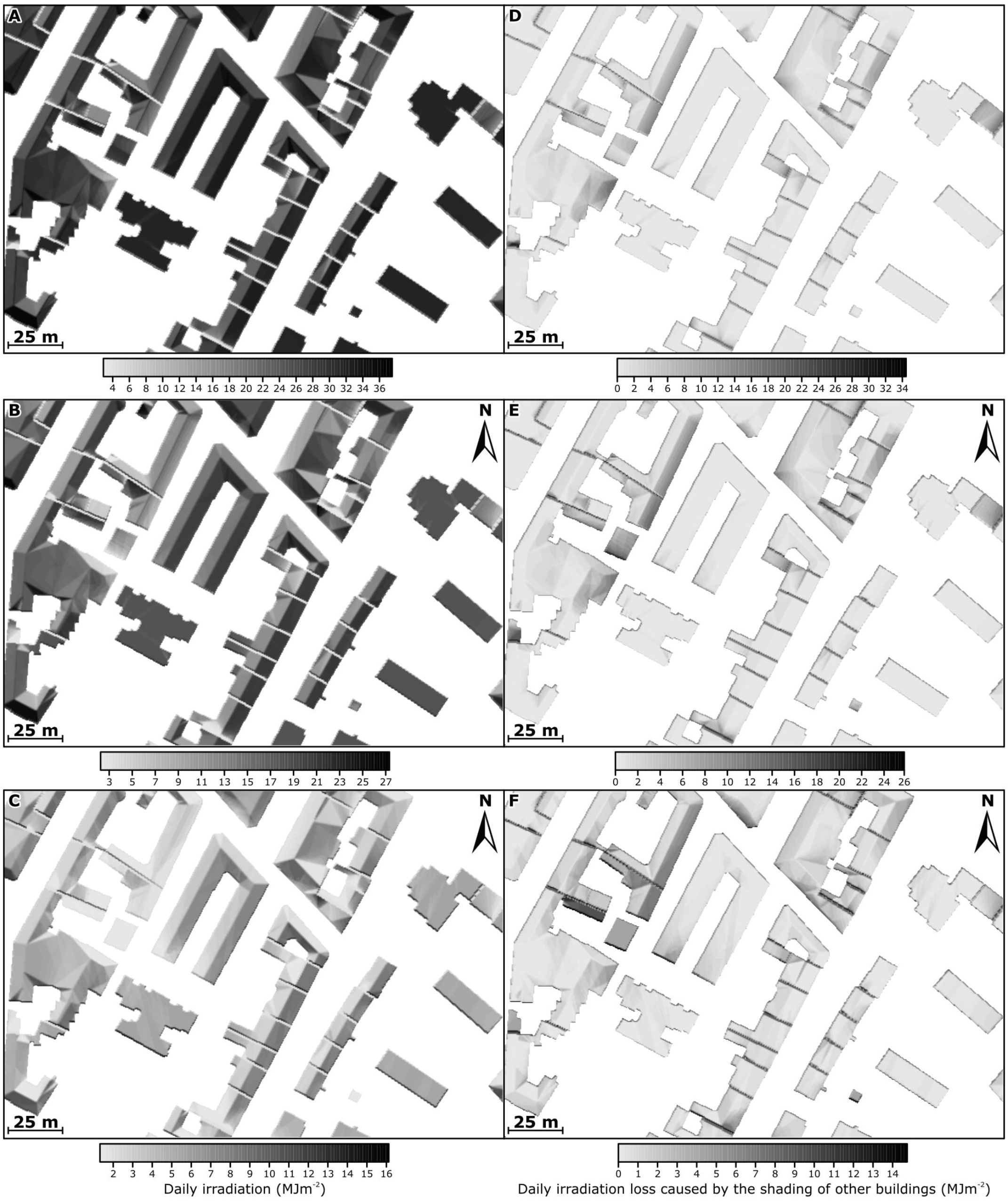

Figure 3: Daily amount of the irradiation in the study area at Summer solstice (A), at March-September equinoxes (B), at Winter solstice (C) and the daily irradiation loss caused by the shading of the surrounding buildings at Summer solstice (D), at March-September equinoxes (E), at Winter solstice (F).

Table 1. Descriptive statistics of the daily amount of irradiance and the daily irradiation loss caused by the shading of the surrounding buildings in the calculation and study areas

	Season	$K\downarrow_{shade}$ (MJm^{-2})			$K\downarrow_{no\text{-}shade} - K\downarrow_{shade}$ (MJm^{-2})	
		min	mean	max	mean	max
Calculation area	summer	2.88	25.12	37.68	2.28	34.75
	spring, autumn	2.25	14.71	28.11	2.29	25.78
	winter	1.32	5.07	16.29	1.79	14.72
Study area	summer	2.88	25.17	37.53	2.59	34.46
	spring, autumn	2.25	14.66	27.24	2.57	25.78
	winter	1.32	4.69	16.12	1.94	14.72

The total potential daily amount of irradiance on the roofs in the study area is 70 182 MJ at Winter solstice, 219 407 MJ at Spring and Autumn equinoxes and 376 748 MJ at Summer solstice.

4. Conclusions

The presented method is a useful tool for calculating the daily amount of the irradiance in urban areas concentrating on rooftops. Based on the obtained values photovoltaic potential of the buildings in an urban district can be estimated and this method also helps to localize the most suitable places for the installation of solar systems on roofs. Our results also reveal the importance of the effect of mutual shading on the possible solar energy gain in urban areas.

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